TECHNICAL SUPPORT DOCUMENT FOR PROCESS EMISSIONS FROM ELECTRONICS MANUFACTURE (SEMICONDUCTORS, MEMs, LIQUID CRYSTAL DISPLAYS, AND PHOTOVOLTAICS):

PROPOSED RULE FOR MANDATORY REPORTING OF GREENHOUSE GASES

Office of Air and Radiation

U.S. Environmental Protection Agency

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Contents

1. Source Description

The electronics industry uses multiple long-lived fluorocarbons (FCs) during manufacturing of electronic devices, including semiconductors, liquid crystal displays (LCD), microelectromechanical systems (MEMs), and photovoltaic (PV) products.[1] FC gases are used for plasma etching of silicon materials, and cleaning silicon deposits on deposition tool chamber walls. Additionally, semiconductor manufacturing employs FC liquids as heat transfer fluids (HTFs). The most common FC gases in use are trifluoromethane (HFC-23 or CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6), and nitrous oxide (N_2O), although other compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used (EPA, 2008a). Besides dielectric film etching and chamber cleaning, much smaller quantities of fluorinated gases are used to etch polysilicon films and refractory metal films like tungsten. PFCs may also be used during dry photoresist stripping, a process also known "ashing." Table 1 presents the FCs used during manufacture of each of these electronics.

Table 1. FCs Used by the Electronics Industry

Product Type	FCs Used During Manufacture
Semiconductor	CF_4, C_2F_6, C_3F_8, c-C_4F_8, c-C_4F_8O, C_4F_6, C_5F_8, CHF_3, CH_2F_2, NF_3, SF_6, and HTFs.[a]
MEMs[b]	CF_4, c-C_4F_8, and SF_6
LCD	CF_4, CHF_3, c-C_4F_8, NF_3, and SF_6
PV	CF_4, C_2F_6, CHF_3, C_3F_8, NF_3, SF_6

[a] For commonly used heat transfer fluids please refer to the U.S. EPA report entitled "Uses and Emissions of Liquid PFC Heat Transfer Fluids" available at: http://www.epa.gov/semiconductor-pfc/documents/pfc_heat_tranfer_fluid_emission.pdf.
[b] IPCC guidelines do not specify the FCs used by the MEMs industry. Literature reviews revealed that CF_4, SF_6, and the Bosch process (e.g., Bosch process consists of alternating steps of SF_6 and C_4F_8) are used to manufacture MEMs.
Source: IPCC, 2006; Lyshevshi, S., 2001; Gaitan, M. & Takacs, M., 2008.

- The etching process uses plasma-generated fluorine atoms, which chemically react with exposed dielectric film, to selectively remove the desired portions of the film. The material removed as well as undissociated fluorinated gases flow into waste streams and, unless emission abatement systems are employed, into the atmosphere.

- Chambers used for depositing dielectric films are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. Undissociated fluorinated gases and other products pass from the chamber to waste streams and, unless abatement systems are employed, into the atmosphere.

- In addition to emissions of unreacted gases, some fluorinated compounds can also be transformed in the plasma processes into different fluorinated compounds which are then exhausted, unless abated, into the atmosphere. For example, when C_2F_6 is used in cleaning or etching, CF_4 is generated and emitted as a process by-product.

- Additionally, FC liquids are used as heat transfer fluids (HTFs) at several semiconductor facilities to cool process equipment, control temperature during device testing, and solder semiconductor devices to circuit boards, and their high vapor pressures can lead to evaporative losses during use (EPA, 2008b; IPCC, 2006).

a. Total U.S. Emissions

Emissions of FCs from an estimated 216 electronics facilities were estimated to be 6.0 Tg CO_2 Eq. Below is a breakdown of emissions by electronics product type.

[1] The electronics industry as defined here does not include light emitting diodes (LEDs). LED manufacturers do not use silicon semiconductor substrates; therefore it is reasonable to conclude that LED manufacturers do not use PFCs.

- Semiconductor: Emissions of FCs, including heat transfer fluids, from 175 facilities were estimated to be 5.7 Tg CO_2 Eq. in 2006 (Burton, C.S., & Beizaie, R., 2001; ITRS, 2007; SEMI, 2007; VLSI Research, Inc., 2007).[2] Of the total semiconductor emissions 5.1 Tg CO_2 Eq. are from etching/chamber cleaning at full-scale facilities, 0.1 Tg CO_2 Eq. are from etching/chamber cleaning at R&D and pilot facilities and 0.5 Tg CO_2 Eq. are from HTF usage from all facilities.[3] Only etching/cleaning emissions from full-scale facilities are accounted for in the *U.S. Inventory of GHG Emissions and Sinks* (EPA, 2008a). Partners of the *PFC Reduction/Climate Partnership for Semiconductors* comprise approximately 80% of U.S. semiconductor production capacity. These Partners have committed to reduce their emissions (exclusive of HTF emissions) to 10% below their 1995 levels by 2010, and their emissions have been on a general decline toward attainment of this goal since 1999.

- MEMs: Emissions of FCs from 12 facilities were estimated to be 0.1 Tg CO_2 Eq. in 2006 (SEMI, 2007).[4,5]

- LCD: Emissions of FCs from 9 facilities were estimated to be 0.02 Tg CO_2 Eq. in 2006 (DisplaySearch, 2007).[6]

- PV: Emissions of FCs from 20 PV facilities were estimated to be 0.07 Tg CO_2 Eq. in 2006 (Burton, 2006; Roedern, B.V. & Ullal, H.S., 2008; Earth Policy Institute, 2007).[7]

b. Emissions to be Reported

On-site combustion emissions from electronics manufacturing facilities are not addressed within this document; see the background Technical Support Document for Stationary Combustion (EPA-HQ-OAR-2008-0508-004). EPA is requiring the electronics industry report direct FC emissions from the following two processes.

- Plasma etching.
- Chamber cleaning.

Additionally, the EPA is proposing to require that facilities report direct FC emissions from the following activity.

- Heat Transfer Fluid Use.

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[2] Total semiconductor facilities include both full-scale, pilot, and R&D facilities.

[3] All full scale facilities are assumed to have the same utilization. R&D and pilot facilities are also assumed to have the same utilization but are assumed to be $1/5^{th}$ the utilization of full scale facilities.

[4] The estimated total number of MEMs facilities in the U.S. is an underestimate. The estimate was based on the World Fab Watch database, which provides an incomplete listing of total U.S. MEMs facilities (SEMI, 2007).

[5] Because no IPCC Tier 1 default emission factor relative to the area of the substrate for MEMs exists, one was estimated. Assuming that MEMs are made from using the Bosch etching process, the utilization of SF_6 in the production of MEMs was assumed to be the same as the utilization of SF_6 in the etching of semiconductors due to the similarity between the two processes. Although the Bosch etching process uses both SF_6 and C_4F_8, C_4F_8 was not included because C_4F_8 has a high utilization rate, i.e., a high fraction of C_4F_8 is dissociated during the etching or cleaning process. The vast majority (86%) of SF_6 used in semiconductor manufacturing process is used in the etching process. The Tier 1 emission factor (per area of substrate) for each electronics product is related both to the utilization and quantity of each type of gas used to make that product. Because SF_6 is used in only about 20% of semiconductor processes but it is assumed here that it is used in all MEMs processes, the semiconductor emission factor (per area of substrate) was multiplied by five to estimate the MEMs emission factor per area of substrate.

[6] Estimated total LCD facilities include LCOS, a-Si TFT-LCDs, OLEDs (assuming active matrix), HTPS, TFT, Single Crystal AMLCD, LTPS facilities. Where, TFT = Thin Film Transistor; LCOS = Liquid Crystal on Silicon; a-Si = amorphous silicon; OLED = Organic Light Emitting Diode; HTPS = High Temperature Polysilicon; and AMLCD = Active Matrix Liquid Crystal Display.

[7] Estimated total PV facilities includes only silicon based PV facilities (both crystalline and amorphous silicon based PV facilities are included).

2. Options for Reporting Threshold

EPA evaluated a range of threshold options for electronics manufacture. These included emission thresholds of 1,000, 10,000, 25,000, and 100,000 metric tons CO_2e and equivalent production capacity-based thresholds for each type of electronics device. (The capacities equivalent to 25,000 mtCO2e are listed in Table 2 below.) Annual production capacity thresholds were derived using IPCC Tier 1 default emissions factors. Where IPCC Tier 1 default factors were unavailable (i.e., MEMs), the emissions factor was estimated based on those of semiconductors for the relevant FCs.

Table 2 shows the capacity-based thresholds equivalent to 25,000 $mtCO_2e$ for each electronics sector. These thresholds are estimated to cover about 50% of semiconductor facilities and between 5% and 17% of the facilities manufacturing other types of electronics. At the same time, the thresholds are expected to cover over 96% of FC emissions from semiconductor facilities, and between 47% and 66% of FC emissions from facilities manufacturing other types of electronics. Combined, these emissions are estimated to account for close to 94% of FC emissions from electronics as a whole.

Table 2. Capacity-Based Threshold (25,000 $mtCO_2e$)

Threshold Level	Total National Emissions ($mtCO_2e$)	Total National Facilities	Emissions Covered		Facilities Covered	
			$mtCO_2e$/yr	Percent	Facilities	Percent
Semiconductors 1,080 m^2 silicon	5,741,676	175	5,492,066	95.7%	91	52.0%
MEMs 1,020 m^2 silicon	146,115	12	96,164	65.8%	2	16.7%
Flat Panel Displays 235,700 TFT-FPD m^2	23,632	9	0	0%	0	0%
Photovoltaics 728,000 PV-cell m^2	73,038	20	34,340	47%	1	5.0%

Table 3 shows emissions and facilities that would be captured by capacity-based thresholds equivalent to 1,000, 10,000, 25,000, and 100,000 metric tons of CO_2e.

Table 3. Capacity-Based Thresholds for Electronics Manufacture (1,000, 10,000, 25,000, and 100,000 $mtCO_2e$)

Threshold Level ($mtCO_2e$)[a]	Total National Emissions ($mtCO_2e$)	Total National Facilities	Emissions Covered		Facilities Covered	
			$mtCO_2e$/yr	Percent	Facilities	Percent
1,000	5,984,463	216	5,951,863	99.5%	163	75.5%
10,000	5,984,463	216	5,744,213	96.0%	113	52.3%
25,000	5,984,463	216	5,622,570	94.0%	94	43.5%
100,000	5,984,463	216	4,698,665	78.5%	54	25.0%

[a] Capacity based threshold equivalents to the 1,000, 10,000, 25,000, and 100,000 $mtCO_2e$ for the semiconductor industry are 40, 430, 1,080, 4,310 m^2 Si, for MEMs manufacture are 40, 410, 1,020, 4,100 m^2 Si, for FPD manufacture are 9,430, 94,300, 235,700, 943,000 m^2 TFT-FPD substrate, and for PV manufacture are 29,120, 291,200, 728,00, 2,912,100 m^2 PV-cell respectively.

Table 4 shows emissions and facilities that would be captured by emissions thresholds of 1,000, 10,000, 25,000, and 100,000 metric tons of CO_2e.

Table 4. Emissions-Based Thresholds for Electronics Manufacture (1,000, 10,000, 25,000, and 100,000 $mtCO_2e$)

Threshold Level ($mtCO_2e$)[a]	Total National Emissions ($mtCO_2e$)	Total National Facilities	Emissions Covered		Facilities Covered	
			$mtCO_2e$/yr	Percent	Facilities	Percent
1,000	5,984,463	216	5,966,476	99.7%	157	72.7%
10,000	5,984,463	216	5,681,001	94.9%	83	38.4%
25,000	5,984,463	216	5,324,624	89.0%	61	28.2%
100,000	5,984,463	216	2,799,814	46.8%	15	6.9%

Capacity-based thresholds would permit facilities to quickly determine whether or not they must report under this rule. In addition, semiconductor manufacturers in particular may employ emissions abatement equipment (e.g., thermal oxidizers) to lower their FC emissions. When abatement equipment is used, semiconductor manufacturers often estimate their emissions using the manufacturer published Destruction or Removal Efficiency (DRE) for the equipment. However, abatement equipment may fail to achieve its rated DRE for two reasons. First, the equipment may not be properly operated and maintained. Second, the DRE itself may have been incorrectly measured due to a failure to account for the effects of dilution (e.g., CF_4 can be off by as much as a factor of 20 to 50 and C_2F_6 can be off by a factor of up to 10 because of failure to properly account for dilution [Burton, 2007].) In either event, the actual emissions from facilities employing abatement equipment may exceed estimates based on the rated DREs of this equipment and may therefore exceed the $mtCO_2e$ threshold without the knowledge of the facility operators. Reporting is therefore important for verifying the performance of abatement equipment where it is used.

3. Options for Monitoring Methods

EPA reviewed a range of protocols for estimating fluorinated GHG emissions from electronics manufacturing. These included the *2006 IPCC Guidelines*, EPA's *PFC* Reduction/Climate Partnership for the Semiconductor Industry, the Technical Guidelines for the Voluntary Reporting of Greenhouse Gases (1605(b) Program), EPA's Climate Leaders Program, The Climate Registry, the WRI/WBCSD *Greenhouse Gas Protocol*, and the World Semiconductor Council methods.

The methods described in these protocols and guidelines coalesce around the methods described by the 2006 IPCC guidelines. For monitoring emissions of fluorinated GHGs from etching and cleaning, EPA evaluated the IPCC Tier 1, Tier 2a, Tier 2b, and Tier 3 approaches, as well as hybrids of these approaches, as described below. For monitoring emissions of heat transfer fluids, EPA evaluated the IPCC Tier 1 and Tier 2 approaches.

None of the IPCC methods require a standard protocol to estimate DREs of abatement equipment. Given that the actual DRE of the abatement equipment can be significantly smaller (by up to a factor of 50) compared to the manufacturer rated DRE, the EPA is considering requiring verification of the DREs using a standard reporting protocol (Burton, 2007). A draft of such a standard protocol is under development by the EPA (not yet published).

a. Etching and Cleaning

In the Tier 1 approach, the surface area of substrate (e.g., silicon, LCD or PV-cell) produced during manufacture is multiplied by a default gas-specific emission factor. The advantages of the Tier 1 approach lie in its simplicity. However, this method does not account for the differences among process types (i.e., etching versus cleaning), individual processes, or tools, leading to uncertainties in the default emission factors of up to 200% at the 95% confidence interval (IPCC, 2006).8 Moreover, facilities routinely monitor gas consumption in the ordinary course of business, making it technically feasible to employ a method with the complexity of at least the IPCC Tier 2a approach without additional data collection efforts.

[8] This uncertainty refers only to semiconductors and LCDs. Tier 1 emission factor uncertainty for PV were not estimated in the IPCC Guidelines (IPCC, 2006).

In the Tier 2a approach, chemical-specific gas consumption is multiplied by default factors for utilization, by-product formation, and destruction. The Tier 2a approach is relatively-simple, given that gas consumption data is collected in the ordinary course of business. However, due to variation in gas utilization between etching and cleaning processes, the emissions estimated using the Tier 2a approach have greater uncertainty than emissions estimated using the Tier 2b approach.

In the Tier 2b approach, chemical-specific gas consumption by process type (i.e. etch or chamber clean) is multiplied by default factors for utilization, by-product formation, and destruction. The Tier 2b approach requires facilities to determine gas consumption by process-type (i.e., etch versus clean). Equation 1 below is used to estimate FC emissions during process (j) for gas (i), and Equation 2 below is used to estimate byproduct gas (p) that results from gas (i) utilization during process (j).

Equation 1) $E(FC)_{i,j} = FC_{i,j} (1 - U_{i,j}) \times (1 - a_{i,j} \times d_{i,j})$

where,
$E(FC)_{i,j}$ = emissions of gas (i) used in process (j), kg
$FC_{i,j}$ = consumption of gas (i) for process (j), kg
$U_{i,j}$ = process utilization rate for gas (i) during process (j)
$a_{i,j}$ = fraction of gas (i) used in process (j) with abatement devices
$d_{i,j}$ = fraction of gas (i) destroyed in abatement devices connected to process (j)

Equation 2) $B(FC)_{i,j} = Bp_{,i,j} \times FC_{i,j} \times (1 - a_{i,j} \times dp_{,j})$

where,
$B(FC)_{p,i,j}$ = by-product gas (p) emissions from gas (i) used in process (j), kg
$Bp_{,i,j}$ = fraction of gas (p) created during gas (i) in process (j)
$FC_{i,j}$ = consumption of gas (i) for process (j), kg
$a_{i,j}$ = fraction of gas (i) used in process (j) with abatement devices
$dp_{,j}$ = fraction of gas (p) destroyed in abatement devices connected to process (j)

The heel "h" has been removed from the equation here, since it is assumed that facilities will estimate their FC usage using flow meters or process recipes (and duration of the process) when estimating their emissions. In this case, heel estimates are not required. However, if gas consumption is estimated using gas cylinders, both Equations 1 and 2 must be multiplied by one minus a heel factor to account for gas remaining in cylinders at the end of life. The IPCC 2006 default for the heel factor is 0.1 (IPCC, 2006).

Although the uncertainty relative to Tier 2a is reduced, the Tier 2b approach does not account for variation among individual processes or tools and, therefore, the estimated emissions have approximately 3-4 times as high uncertainty compared to Tier 3 estimates. The Tier 2b total FC emissions estimate uncertainty is approximately ±51%. For a typical large fab with emissions of approximately 113,000 mtCO2e, this relative uncertainty equates to an absolute uncertainty of ±58,000 $mtCO_2e$.

The Tier 3 approach uses the same equations as the Tier 2b approach, but requires company-specific data on (1) gas consumption, (2) gas utilization, (3) by-product formation, and (4) DRE for all processes at the facility. The use of the Tier 3 method will result in the least uncertain estimates. Information on gas consumption by process is sometimes gathered in the ordinary course of business, and information on gas utilization and by-product formation is readily available from tool manufacturers. In addition, gas utilization and byproduct formation can be experimentally measured on-site at the facility (International Sematech, 2006). To obtain accurate estimates of these parameters, the guidance prepared by International SEMATECH Technology Transfer (#0612485A-ENG) should be followed when conducting gas utilization and by-product formation measurements (December 2006).

The total facility-level FC emissions estimate from etching/cleaning using Tier 3 analysis is estimated to have an uncertainty on the order of ±15% at the 95% confidence interval (IPCC, 2006). For a typical large fab with emissions of approximately 113,000 mtCO2e, this relative uncertainty equates to an absolute uncertainty of ±17,000 $mtCO_2e$.

Hybrid Approach A would require large facilities (defined as facilities with capacities of greater than 10,500 m2 silicon) to estimate their etching and cleaning emissions using an approach based on the IPCC Tier 3 method; all other facilities would

be required to use the IPCC Tier 2b method. Under these approaches, EPA estimates that 17% of all semiconductor manufacturing facilities would be required to report using a Tier 3 approach (equivalent to 29 entities out of 175 total entities) and that 58% of total semiconductor emissions (equivalent 3.3 Tg CO2 Eq out of a total 5.7 Tg CO2 Eq emissions) would be reported using the Tier 3 approach.

Hybrid Approach B would require Tier 3 reporting for all facilities, but only for the top three gases emitted at each facility. For all other gases, the Tier 2b approach would be required. The top three gases emitted, based on data in the Inventory of U.S. GHG Emissions and Sinks, are C_2F_6, CF_4, and SF_6 (EPA, 2008a). These top three gases accounted for approximately 80% of total FC emissions from semiconductor manufacturing during etching and chamber cleaning in 2006. The uncertainty associated with the Tier 2b/3 hybrid approach has not been developed, but is assumed to be between the uncertainty for a Tier 2b and Tier 3 approach.

Verifying the DRE of Abatement Equipment. As mentioned above, EPA has evaluated additional requirements for verifying the DRE of abatement equipment. Both of the approaches evaluated would require that the DRE be verified using an industry standard or protocol, such as the one being developed by the EPA as part of the PFC Reduction/Climate Partnership for Semiconductors. (This standard has not yet been published). This draft protocol requires the person verifying the DRE to experimentally determine the effective dilution of the waste stream as it travels through the abatement device and to measure the DRE during representative actual or simulated process conditions. The following measurements and calculations are critical to the protocol:

(1) Experimentally determine the effective dilution through the abatement device and measure abatement DRE during actual or simulated process conditions by following the procedures of this paragraph.

(i) Measure the concentrations of F-GHGs exiting the process tool and entering and exiting the abatement system under operating process and abatement system conditions that are representative of those for which F-GHG emissions are estimated and abatement-system DRE is used for the F-GHG reporting period[9];

(ii) Measure the dilution through the abatement system and calculate the dilution factor under the representative operating conditions given in paragraph (c)(i) of this section by using the tracer method. This method consists of injecting known flows of a non-reactive gas (such as krypton) at the inlet of the abatement system, measuring the time-averaged concentrations of krypton entering ($[Kr]_{in}$) and exiting ($[Kr]_{out}$) the abatement system, and calculating the dilution factor (DF) as the ratio of the time-averaged measured krypton concentrations entering and exiting the abatement system, using equation I-10 of this section.

$$DF = \frac{[Kr]_{in}}{[Kr]_{out}}$$

(iii) Measure the F-GHG concentrations in and out of the device with all process chambers connected to the F-GHG abatement system and under the production and abatement system conditions for which F-GHG emissions are estimated for the reporting period[10];

(iv) Calculate abatement system DRE using Equation I-11 of this section, where it is assumed that the measurement pressure and temperature at the inlet and outlet of the abatement system are identical and where the relative precision (ε) of the quantity $c_{i\text{-}out}$*DF/$c_{i\text{-}in}$ shall not exceed ±10% (two standard deviations) using proper statistical methods.

$$d_{ij} = 1 - \frac{DF * c_{i-out}}{c_{i-in}}$$

Where:

[9] Abatement system means a point-of-use (POU) abatement system whereby a single abatement system is attached to a single process tool or single process chamber of a multi-chamber tool.

[10] Most process tools have multiple chambers. For combustion-type abatement systems, the outlets of each chamber separately enter the destruction-reactor because premixing of certain gaseous mixtures may be conducive to fire or explosion. For the less-frequently used plasma-type POU abatement systems, there is one system per chamber.

d_{ij} = Destruction or removal efficiency (DRE)

$c_{i\text{-}in}$ = Concentration of gas i in the inflow to the abatement system (ppm).

$c_{i\text{-}out}$ = Concentration of gas i in the outflow from the abatement system (ppm).

DF = Dilution Factor calculated using Equation I-10.

(v) The DF should not be obtained by calculation from flows other than those obtained by using the tracer method described in paragraph (ii).

The difference between the two approaches lies in who performs the test. In the first approach, each facility would perform the test on site for each piece of abatement equipment. In the second approach, a third party (e.g., Underwriters Labs) would perform the test on behalf of the manufacturer of the abatement equipment, testing representative samples of the abatement equipment. Under this approach, electronics manufacturing facilities would be required to buy equipment that had been certified under this third-party testing. Because testing would not need to be obtained for every piece of equipment sold, this approach would probably be less expensive than in-house testing by electronics manufacturers, but it may not capture the full range of conditions under which the abatement equipment would actually be used. Facilities pursuing either DRE verification method would also be required to use the equipment within the manufacturer's specified equipment lifetime, operate the equipment within manufacturer specified limits for the gas mix intended for destruction, and maintain the equipment according to the manufacturer guidelines.

b. Nitrous Oxide (N_2O) Emissions

A simple mass-balance approach is proposed to estimate emissions of N2O during chemical vapor deposition, as shown in Equation 4. This methodology assumes N2O is not utilized during this process, due to lack of N2O utilization data.

Equation 3) $E(N_2O) = FC_{N2O} \times (1\text{-}h)$

where,
$E(N_2O)$ = Emissions of N_2O, kg
FC_{N2O} = Consumption of N_2O, kg
h = heel fraction of gas in cylinders

c. Heat Transfer Fluids (HTFs)

The Tier 1 approach for HTF emissions is based on the utilization capacity of the semiconductor facility multiplied by a default emission factor. Although, the Tier 1 approach has the advantages of simplicity, it relies on a default emissions factor to estimate HTF emissions and has relatively high uncertainty compared to the Tier 2 approach (IPCC, 2006).

The IPCC Tier 2 approach, which is a mass-balance approach, uses company-specific data and accounts for differences among facilities' HTFs (which vary in their global warming potentials), leak rates, and service practices, and has an uncertainty on the order of ±20% at the 95% confidence interval (IPCC, 2006). Equation 3 below shows the company-specific mass-balance equation for estimating HTF emissions.

Equation 4) E(HTFi) = density x [Ii,o + Pi,t - Ni,t + Ri,t - Ii,t - Di,t]

where,
E(HTFi) = Emissions of heat transfer fluid (i) (HTFi), kg
density = density of HTFi, kg/l
Ii,o = Inventory of HTFi at the end of previous period, l
Pi,t = Net purchases of HTFi during the current period, l
Ni,t = Total nameplate capacity [charge] of installed liquid HTFi equipment, l
Ri,t = Total nameplate capacity [charge] on retired liquid HTFi equipment, l
Ii,t = Inventory of liquid HTFi at the end of current period, l
Di,t = Amount of liquid HTFi recovered and sent offsite during current period, l

4. Procedures for Estimating Missing Data

When estimating etching/cleaning emissions and company-specific process gas utilization rates and by-product gas formation rates are missing, companies could apply defaults from next lower Tier (e.g., IPCC Tier 2b or Tier 2a) to estimate missing data. However, companies should limit their use of using defaults from the next lower Tier to less than 5 percent of their emissions estimate. Additionally, default values for estimating DRE will not be permitted, and DREs must be estimated as zero in the absence of facility-specific DREs that have been third-party verified and/or use a standard protocol. Gas consumption is collected as BAU and is not expected to be missing; therefore, it should not be necessary to revert to the Tier 1 approach for estimating emissions. When estimating HTF emissions during semiconductor manufacture, the use of the mass-balance approach requires correct records for all inputs. Should the facility be missing records for a given input, it may be possible that the HTF supplier has information in their records for the facility.

5. QA/QC Requirements

QA/QC methods for reporting emissions from etching and cleaning include:

- Following the SEMATECH guidelines for QA/QC procedures when estimating gas process utilization and by-product gas formation (International Sematech, 2006).
- Keeping record logs of abatement device maintenance.
- Tracking gas consumption is done as BAU to a high-degree of precision, and further QA/QC is not being required.

QA/QC methods for reporting emissions from HTFs from semiconductors include:

- Reviewing inputs to the mass balance equation to ensure inputs and outputs to the facility's system are all accounted for in all appropriate sections.
- Ensuring no negative inputs are entered and negative emissions are not calculated. However, the *change* in storage inventory and nameplate capacity may be calculated as negative numbers.
- Ensuring that beginning of year inventory matches end of year inventory from previous year.

6. Reporting Procedures

The following supplemental data would be useful for confirming emissions calculations and/or calculating emission rates that could be compared across facilities for quality control purposes:

- Report:
    - Method used (i.e. 2b or 3)
    - Mass of each gas fed into each process type (kg)
    - GWPs for each FC used/created as a by-product
    - Production capacity in terms of substrate surface area (e.g., silicon, PV-cell, LCD)
    - Factors used for gas utilization, by-product formation and their sources/uncertainties
    - Emission control technology DREs and their uncertainties
    - Fraction of gas fed into each process type with emission control technologies
    - Abatement device calibration/maintenance records
    - Description of abatement controls
    - Inputs in the mass-balance equation (for HTF emissions)
    - Example calculation
    - Description of QA/QC plan
    - Emissions uncertainty estimate

- Keep records of:
    - Data actually used to estimate emissions
    - Records supporting values used to estimate emissions
    - The initial and any subsequent tests of the abatement equipment's destruction or removal efficiency (DRE)

- The initial and any subsequent tests to determine emission factors for process

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Appendix A

		Greenhouse Gases with TAR GWP									Greenhouse Gases without TAR GWP			Non-GHGs Producing FC By-products‡	
	Process Gas	CF4	C2F6	CHF3	CH2F2	C3F8	c-C4F8	NF3 Remote	NF3	SF6	C4F6	C5F8	C4F8O	F2	COF2
SEMICONDUCTOR MANUFACTURING	Etch 1-Ui	0.7*	0.4*	0.4*	0.06*	NA	0.2*	NA	0.2	0.2	0.1	0.2	NA	NA	NA
	CVD 1-Ui	0.9	0.6	NA	NA	0.4	0.1	0.02	0.2	NA	NA	0.1	0.1	NA	NA
	Etch BCF4	NA	0.4*	0.07*	0.08*	NA	0.2	NA	NA	NA	0.3*	0.2	NA	NA	NA
	Etch BC2F6	NA	NA	NA	NA	NA	0.2	NA	NA	NA	0.2*	0.2	NA	NA	NA
	CVD BCF4	NA	0.1	NA	NA	0.1	0.1	0.02†	0.1†	NA	NA	0.1	0.1	0.02†	0.02†
	CVD BC2F6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	CVD BC3F8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.04	NA	NA
LCD MANUFACTURING	Etch 1-Ui	0.6	NA	0.2	NA	NA	0.1	NA	NA	0.3	NA	NA	NA	NA	NA
	CVD 1-Ui	NA	NA	NA	NA	NA	NA	0.03	0.3	0.9	NA	NA	NA	NA	NA
	Etch BCF4	NA	NA	0.07	NA	NA	0.009	NA	NA	NA	NA	NA	NA	NA	NA
	Etch BCHF3	NA	NA	NA	NA	NA	0.02	NA	NA	NA	NA	NA	NA	NA	NA
	Etch BC2F6	NA	NA	0.05	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	CVD BCF4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	CVD BC2F6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	CVD BC3F8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PV MANUFACTURING	Etch 1-Ui	0.7	0.4	0.4	NA	NA	0.2	NA	NA	0.4	NA	NA	NA	NA	NA
	CVD 1-Ui	NA	0.6	NA	NA	0.1	0.1	NA	0.3	0.4	NA	NA	NA	NA	NA
	Etch BCF4	NA	0.2	NA	NA	NA	0.1	NA	NA	NA	NA	NA	NA	NA	NA
	Etch BC2F6	NA	NA	NA	NA	NA	0.1	NA	NA	NA	NA	NA	NA	NA	NA
	CVD BCF4	NA	0.2	NA	NA	0.2	0.1	NA	NA	NA	NA	NA	NA	NA	NA
	CVD BC2F6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	CVD BC3F8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Notes: NA denotes not applicable based on currently available information

‡ The default emission factors for F2 and COF2 may be applied to cleaning low-k CVD reactors with ClF3.

* Estimate includes multi-gas etch processes

† Estimate reflects presence of low-k, carbide and multi-gas etch processes that may contain a C-containing FC additive

Source: IPCC, 2006